

Energy-efficient MAC Protocol using Directional Antennas in IEEE 802.11- Based Wireless Sensor Networks

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Abstract – This paper presents an energy-efficient medium access control (MAC) protocol using directional antennas in IEEE 802.11- based wireless sensor networks. In the IEEE 802.11 standard, every transmitted frame has duration value (DV). The DV indicates the time needed to transmit remaining segments and acknowledgement frame. However, packet corruption, poor link quality and multipath propagation may affect the initial predicted transmission time, and this may lead to inefficient duty cycling by neighboring sensor nodes. The new DV-based MAC (DV-MAC) protocol addresses this concern by developing a new approach for estimating effective DV, thereby providing more efficient duty cycling for wireless sensor nodes and reducing interference(s) from neighbouring sensor nodes of the receiver sensor node. The efficacy of this protocol is tested via numerical analysis which is implemented in Visual C++ and MATLAB Software. It is shown by the results obtained that this new protocol will further improve energy efficiency by reducing interferences in wireless sensor networks.

Keywords – Directional Antennas, Duration Value, Frame, Transmission, Reception, MAC Protocol, Wireless Sensors.

I. INTRODUCTION

In this paper, wireless sensor networks are based on the IEEE 802.11 standard [1]. In this standard's specifications, there is a duration field of two octets (16 bits) in the MAC frame header and the individual frame at the MAC sub-layer. The value inserted in this field is called duration value (DV). All DVs are calculated in microseconds. The DV indicates the time needed to transmit all the remaining segments and acknowledgment (ACK) frame. It is stored by every sensor node in a variable called a Network Allocation Variable (NAV). Each sensor node maintains the NAV to monitor the activities in its neighbourhood. A timer is set in every node to monitor the value stored in the NAV; and whenever a node has data to send, it must first check its NAV. An important function of MAC protocol is to prevent collisions by ensuring that interfering nodes do not transmit signals at the same time. Whereas the MAC sub-layer determines how data is sent through the physical channels, the physical (PHY) layer consists of antennas which comprise of the physical hardware of transmission system. On the one hand, the IEEE 802.11 assumes omnidirectional antennas for nodes in wireless sensor networks. Since omnidirectional antennas spread radio signals in all directions, the capacity of wireless networks using omnidirectional antennas is limited due to the high interference and the low spatial reuse. On the other hand,

using directional antennas in wireless sensor networks allows more concurrent transmissions in the vicinity of a pair of communicating sensor nodes. Since directional antenna allows node to selectively receive signal from a desired direction, it enables the receiver node to avoid interference(s) that comes from unwanted directions, thereby increasing the signal-to-noise ratio (SNR). To best utilize directional antennas however, a suitable MAC protocol must be designed. Current MAC protocols, such as the IEEE802.11, use a handshake mechanism implemented by exchanging small control frames named Request to Send (RTS) and Clear to Send (CTS). The successful exchange of these two control frames reserves the channel for transmission of the data frame and a short acknowledgement (ACK) frame. The RTS and CTS frames contain a duration field that defines the period of time that the medium is to be reserved to transmit the actual data frame and the returning ACK frame. A sensor node intending to send data transmits RTS frame, to which the intended receiver may respond with CTS frame. Once the RTS/CTS handshake is successful, the transmitter sensor node can then transmit the data frame and associated ACK frame to the receiver sensor node. In existing literature, researchers have presented several MAC protocols with different research objectives. For example, a comprehensive overview of MAC protocols was provided in [2]. A PDV-MAC protocol that uses the duration value in transmitted frame to set-up randomised sleep/wake schedules for neighbouring nodes of the receiver sensor node was presented in [3]. The results obtained showed that this MAC protocol can increase energy efficiency by eliminating packet collisions at receiver sensor nodes. Mobile target tracking in wireless sensor networks with uncovered holes was accomplished in [4]. It was shown that the approach could realise the real-time detection of moving object when it runs in and out of the hole, and consume much less energy than the omni-directional antenna- based methods. The problem of determining the number of channels needed to ensure collision-free communications, given a set of wireless sensor nodes equipped with directional antennas was investigated in [5]. In addition, a MAC Protocol named Busy-Tone based directional MAC protocol, which could solve the problem of hidden terminal and deafness with low overhead was presented in [6]. Transmission strategy can be varied according to usage of channel as nodes can send RTS and CTS omnidirectionally or directionally [7]. Moreover, a detailed study on recent advances on directional antennas in wireless sensor networks was

presented in [8]. Using directional antennas in wireless sensor networks can improve network capacity and reduce the end-to-end transmission delay[9]. A real-world antenna prototype was characterized in [10], and applied to an existing wireless sensor network (WSN) stack. The paper was based on prototype called parasitic interference directional antenna presented in [11]. The potential benefit of integrating directional antenna into wireless sensor networks was explored in [12]. A reconfigurable angular diversity antenna with quad-corner reflector arrays and a switching control was constructed in [13]. The system shows a high radiation gain, but occupies a large volume. Moreover, a compact switched-beam antenna was presented in [14]. It is composed of a 4-element antenna array and shows eight directional patterns and an omni-directional one, ensuring uniform coverage of the 360° horizon. In an interesting contribution, a switched-beam directional antenna consisting of four planar patch antennas arranged in a box-like structure was investigated in [15]. This antenna system ensures a uniform coverage of the whole horizon plane when switching between antennas. A linearly polarized pattern reconfigurable microstrip parasitic array was presented in [16]. This antenna is a simple structure but does not ensure 360° degree azimuth coverage. Furthermore, a MAC protocol that addressed the problem of hidden terminals, deafness and determination of neighbours' location was presented in [17]. A beam-forming transmitter scheduling algorithm was developed to prolong the life of wireless sensor network [18]. The algorithm schedules transmitter based on nodes' phase offsets, remaining energy and locations. Moreover, an approach in which the Access Point (AP) sequentially scans the space by forming directional beams and apply contention-free or contention-based user polling within each beam was presented in [19]. A reconfigurable beam-steering antenna, consisting of eight directional radiators and one omni-directional radiator was developed in [20]. In addition to the foregoing, a modified MAC protocols suitable for IEEE802.11- based ad hoc networks using directional antennas was investigated in [21].

The rest of the paper is organized as follows. Motivation and problem definition are presented in Section 2. Problem solution is discussed in Section 3. Numerical analysis and discussion of results as well as contributions of the research work are presented in Section 4. Section 5 concludes the paper.

II. MOTIVATION AND PROBLEM DEFINITION

This research is motivated by the need to further improve energy efficiency by reducing interferences in wireless sensor networks.

A. Problem Definition

DCF is a medium access protocol which allows for automatic medium sharing between compatible physical layers by the use of CSMA/CA and a random back-off time following a busy medium state. Sensor nodes using the DCF may transmit if its carrier sense mechanism determines that the medium is idle. The predicted DV by the directional RTS/CTS mechanism may however change

in the course of data transmission due to some factors (e.g., interferences from neighboring sensor nodes, link quality, etc.) which may affect applicable bits transfer rate, cause packet corruption and may ultimately affect the effective data transmission/reception time. Re-transmission of corrupted segments will also affect estimated duration announced by the virtual carrier sensing mechanism at commencement of transmission (or reception). A practicable solution to this concern (which is implemented in IEEE802.11) is to break the MSDU into smaller fragments. MSDU is contained in the frame body of the MAC data frame and each MSDU transmitted by a wireless sensor node is assigned a sequence number. Whereas fragmentation is the process of partitioning an MSDU into smaller MAC-level frames MPDU, defragmentation is the process of recombining MPDUs into a single MSDU at the immediate receiver sensor node. It should however be noted that the RTS/CTS mechanism is not used for every data frame transmission because the additional RTS/CTS frame will add overhead inefficiency. It is therefore not efficient to deploy multiple RTS and CTS frames in data frames transmission. This informs the need to develop other means of addressing this important concern.

B. Preliminary

Assumptions made in this paper are as follow: (i) the transmitter and receiver sensor nodes are not mobile, and are within communication range of each other, (ii) wireless sensor networks are based on the IEEE 802.11 standard, (iii) only one DA is operational at any point in time, (iv) there is only one scanning cycle in a period of the directional antennas system, (v) the sojourn time in each state of the transceiver subsystem is a random variable with exponential distribution, (vi) no new sensor node joins the network in the middle of ongoing transmission, (vii) a sensor node can get location information of other neighboring nodes by implementing neighbour-discovery methods in the existing literature, and (viii) every sensor node incorporates capability to isolate noise associated with transmitted signal (or received signal). Table I summarizes notations (or abbreviations) used in this paper.

Table I: List of notations (or abbreviations)

Notation	Description
MAC	Medium Access Control
PHY	Physical
RTS	Request to Send
CTS	Clear to Send
ACK	Acknowledgement
DV	Duration Value
NAV	Network Allocation Vector
SIFS	Short Inter-Frame Space
MSDU	MAC Service Data Units
MPDU	MAC Protocol Data Unit
SNR	Signal-to-Noise Ratio
DA _{<i>i</i>}	Directional Antenna <i>i</i>
DCF	Distributed Coordinated Function
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
FCS	Frame Check Sequence
CRC	Cyclic Redundancy Code

The current paper is based on the directional antennas system model presented in Fig.1. The directional antennas system consists of three DAs in which each DA offers 120-degree azimuth-coverage. It is however noted that the MAC protocol presented in this paper can work for other directional antennas systems.

Consider a scenario in which neighbouring nodes (e.g., sensor nodes 1 and 2) receive directional RTS from the transmitter sensor node (i.e., sensor node *T*) or directional CTS from the receiver sensor node (i.e., sensor node *R*). In the IEEE 802.11 standard, nodes 1 and 2 go to sleep for the entire message time based on the initial predicted DV broadcast by the RTS/CTS frame. However, if the transmitter sensor node extends the transmission time due to data packet fragment losses or errors (which require re-transmission), the sleeping neighbouring sensor nodes may not immediately be aware of this transmission extension. For example, if sensor nodes 1 and 2 wake from sleep and transmit frame (or packets) while transmission is ongoing between sensor nodes *T* and *R*, then there will be packet collision at the receiver sensor node due to interferences by packets from sensor nodes 1 and 2.

The MAC protocol presented in this paper uses available information during the exchange of directional RTS and CTS control frames to estimate effective DV, which can accommodate transmission extension.

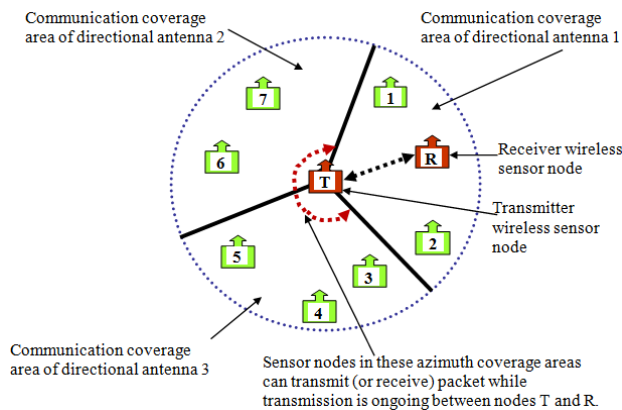


Fig. 1. Sensor node's directional antennas system

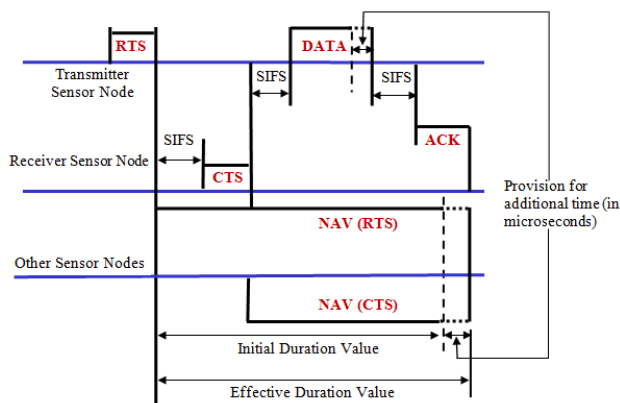


Fig. 2. NAV operation during contention-free period

For directional RTS frame, the duration value is the time (in microseconds) required to transmit the pending data, *plus* one CTS frame, *plus* one ACK frame, *plus* three SIFS intervals. SIFS is the inter-frame spacing prior to transmission of an ACK or a CTS frame. Similarly, for directional CTS frame transmitted in response to RTS frame, the duration value is the value obtained from the duration field of the immediately previous RTS frame, *minus* the time (in microseconds) required to transmit the CTS frame and its SIFS interval.

To better understand the practical operation of the directional antennas system presented in this paper, the block diagram of the radio frequency (RF) switching process is shown in Fig.3. The RF switching system is based on the 74HC4052/74HCT4052 Dual 4-channel analog multiplexer/demultiplexer [22]. The RF input signal is directed to one of the three output lines of the RF switching system using combination of bits on the 2-pin digital interface (i.e., digital select inputs, pins S_0 , and S_1). The digital inputs S_0 and S_1 are used to select destination of the RF input signal. The RF input signal is brought into the switching system using the LOW-enable input line (pin \bar{E}). When pin $\bar{E} = 0$, one of the three directional antennas is selected with pins S_0 and S_1 . It is noted that only three combinations of the digital select bits are used in the current design, in which each combination corresponds to one RF radiating element (i.e., radiating element #1: for DA #1; radiating element #2: for DA #2; and radiating element #3: for DA #3).

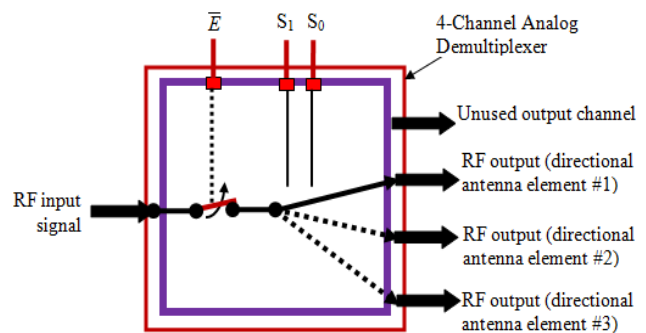


Fig. 3. Block diagram of the radio frequency (RF) switching process of the transceiver subsystem in wireless sensor nodes

The Truth Table of the RF switching system is presented Table II below.

In Table II, when the LOW-enable pin is HIGH, the chip is disabled, hence the "don't care ('x') input on the select pins S_0 and S_1 . It is important to note that the digital inputs 0 and 0 on select pins S_0 and S_1 respectively are not used, hence the hyphen ('-').

Table II: Truth Table of the RF switching system

RF input signal (D)	Enable pin (\bar{E})	Select Pins		RF Output (directional antenna element selected)			
		S_1	S_0	$Y_3(DA_2)$	$Y_2(DA_1)$	$Y_1(DA_0)$	Y_0
D	0	-	-	-	-	-	-
D	0	0	1	0	0	D	0
D	0	1	0	0	D	0	0
D	0	1	1	D	0	0	0
D	1	x	x	0	0	0	0

III. PROBLEM SOLUTION

A. Algorithm for operation of the wireless sensor networks using directional antennas system

The algorithm for the operation of the wireless sensor networks using directional antennas system is presented below:

Step 1: Start, power-ON the transceiver subsystem.

Step 2: The RF switching system selects one RF radiating element (i.e., turn ON one DA) at the transmitter and receiver sensor nodes.

Step 3: Transmitter sensor nodes broadcast directional RTS frame to sensor nodes in a directional coverage area. Information carried by this directional RTS frame includes DV for transmission of remaining segments and acknowledgement frame.

Step 4: The receiver sensor node use the available information to compute SNR; and based on the computed value of SNR, it makes provision for additional transmission (or reception) time. It also uses available information on transmission errors (if any) to make provision for re-transmission as necessary.

Step 5: The receiver sensor node uses the estimated additional transmission time (in microseconds) in *Step 4*, in conjunction with the initial DV to compute effective DV; and then broadcast this effective DV in the duration field of the directional CTS frame to the transmitter sensor node. Neighbouring sensor nodes in directional coverage area of the receiver sensor nodes also receive this directional CTS frame. The transmitter sensor node updates its duration field with this effective DV, and then begins transmission.

Step 6: The neighbouring sensor nodes of the receiver sensor nodes use the effective DV for their duty cycling.

Step 7: End

B. Estimation of effective duration value

For directional CTS frame transmitted in response to directional RTS frame in the IEEE 802.11, the duration value is the value obtained from the duration field of the immediately previous RTS frame, *minus* the time (in microseconds) required to transmit the CTS frame and SIFS interval. Sensor nodes are able to validate every received frame using the FCS. The FCS is a 32-bit field containing a 32-bit CRC, and calculated over all fields of the MAC header and the frame body field. It is noted that CRC can detect data corruption by treating a binary data word as a polynomial with each polynomial coefficient being zero or one, and then performing polynomial

division by a generator polynomial $G(x)$. The remainder of that division operation provides an error detection value that is sent as FCS in the MAC sub-layer frame. A transmission error is declared to have occurred if the stored FCS is not equal to the computed FCS. In the absence of transmission error(s) therefore, the result of the calculation is a unique non-zero remainder value.

Noise may consist of internal noise and environmental noise. The noise added to the signal after the antenna of the receiver sensor node is the internal noise, while the noise from devices outside the network (which may be from electromagnetic noise generated by machinery or radio frequency devices) is called environmental noise. In radio signal reception, noise is the superposition of white noise and other disturbing influences on the information-bearing signal. This may be caused by thermal noise or by interference from radiated electromagnetic noise picked up by the receiver sensor node's antenna. The most common quantity used to determine the quality of a signal at a given point is the signal-to-noise ratio (SNR). SNR is a ratio of the power in a transmitted signal to the power contained in the noise that is present at a particular point in transmission. It is typically measured at the receiver sensor node's antenna. It is noted that whereas CRC can detect data corruption, SNR can set an upper bound on achievable data rate for transmission (or reception). Dynamic switching of transmission data transfer rates can take place at any point in time while transmission is on-going in order to achieve better performance, since physical layer with multi-rate support offers multiple data transfer rates capability. Thus, a wireless sensor node transmitting a frame can select a rate appropriate to current transmission environment based on defined rules of transmission. It is further noted that a high SNR implies high-quality signal reception and vice versa. Moreover, the calculation of the SNR requires information on both the received signal strength and the noise power of the receiver antenna. In this paper, sensor node design integrates instrumentation module to measure received signal strength and noise power.

Let $s_1(t)$ and $s_2(t)$ denotes the directional RTS and CTS signals, and let the associated noise signal be represented by $n_1(t)$ and $n_2(t)$ respectively. Since the value of a signal can be modeled by the energy contained in that signal, the total energy overtime interval $l_1 \leq t \leq l_2$ in continuous-time information-bearing signals $s_1(t)$ and $s_2(t)$, denoted as k_1 and k_2 respectively, are given by

$$k_1 = \int_{l_1}^{l_2} |s_1(t)|^2 dt. \quad (1)$$

and

$$k_2 = \int_{l_1}^{l_2} |s_2(t)|^2 dt. \quad (2)$$

Similarly, the total energy during same time interval $l_1 \leq t \leq l_2$ in continuous-time noise signals $n_1(t)$ and $n_2(t)$, denoted as k_3 and k_4 respectively, are given by

$$k_3 = \int_{l_1}^{l_2} |n_1(t)|^2 dt. \quad (3)$$

and

$$k_4 = \int_{l_1}^{l_2} |n_2(t)|^2 dt. \quad (4)$$

Moreover, the average power dissipated by signals $s_1(t)$ and $s_2(t)$ during time interval $l_1 \leq t \leq l_2$ are computed by

$$m_1 = \frac{1}{(l_2 - l_1)} \int_{l_1}^{l_2} |s_1(t)|^2 dt. \quad (5)$$

and

$$m_2 = \frac{1}{(l_2 - l_1)} \int_{l_1}^{l_2} |s_2(t)|^2 dt. \quad (6)$$

where m_1 and m_2 denotes average power dissipated by information-bearing signals $s_1(t)$ and $s_2(t)$ respectively. Similarly, the average power dissipated by noise signals $n_1(t)$ and $n_2(t)$ during same time interval $l_1 \leq t \leq l_2$ are computed by

$$m_3 = \frac{1}{(l_2 - l_1)} \int_{l_1}^{l_2} |n_1(t)|^2 dt. \quad (7)$$

and

$$m_4 = \frac{1}{(l_2 - l_1)} \int_{l_1}^{l_2} |n_2(t)|^2 dt. \quad (8)$$

where m_3 and m_4 denotes average power dissipated by noise signals $n_1(t)$ and $n_2(t)$ respectively. At the receiver sensor node, the signal-to-noise ratio (SNR) can subsequently be estimated by

$$(SNR)_{dB} = 10 \log_{10} \left(\frac{\text{signal power at receiver's antenna}}{\text{noise power at receiver's antenna}} \right). \quad (9)$$

$$(SNR)_{dB} = 10 \log_{10} \left(\frac{m_1}{m_3} \right). \quad (10)$$

Furthermore, let x_θ^i denotes initial DV in the directional RTS frame, and let y_θ^i denotes estimated additional time for transmission (or reception) extension by sensor nodes using directional antenna i in azimuth-sector θ . If there is data corruption during directional RTS

and CTS frames exchange due to interference from radio frequency device (s) on same network in the neighbourhood of the receiver sensor node, then there is a probability the actual data and ACK frames transmission may be subjected to this same condition. For this reason, the initial DV (i.e. x_θ^i) is updated to provide adequate time for transmission (or reception) extension. Thus, if the CRC in the FCS field of transmitted (or received) frame indicates transmission error(s), then the affected frame shall be re-transmitted. Consequently,

$$\alpha = x_\theta^i + \beta x_\theta^i; \quad 0 < \beta \leq 1. \quad (11)$$

and

$$z_\theta^i = \alpha + y_\theta^i - T_{SIFS}. \quad (12)$$

If no transmission error(s), then

$$z_\theta^i = x_\theta^i + y_\theta^i - T_{SIFS}. \quad (13)$$

where in Equation (12) and (13),

$$y_\theta^i = \begin{cases} \gamma_1; & a \leq (SNR)_{dB} \leq b \\ \gamma_2; & b < (SNR)_{dB} \leq c \\ \gamma_3; & c < (SNR)_{dB} \leq d \\ \gamma_4; & d < (SNR)_{dB} \leq e \end{cases}. \quad (14)$$

Variables a , b , c , d , and e define range of values of $(SNR)_{dB}$; γ_1 , γ_2 , γ_3 , and γ_4 represent additional transmission (or reception) time. Moreover, β (in Equation 11) denotes proportion of initial DV assigned for re-transmission, z_θ^i (in Equations (12) and (13)) is the estimated effective DV inserted in the duration field of the directional CTS frame, and T_{SIFS} denotes SIFS for the directional RTS frame. The receiver sensor node broadcast this estimated effective DV in its directional CTS frame to the transmitter sensor node. Neighboring sensor nodes of the receiver sensor node also receive this directional CTS frame. Each neighboring sensor node uses this effective DV to setup its duty cycling. With this new MAC protocol, neighboring sensor nodes will use the effective (updated) DV to go into sleep mode for period of time long enough for completion of ongoing packet transmission (or reception), thereby preventing interferences. It is expected that the estimated effective DV, which is based on SNR at the receiver sensor node's antenna and available information on transmission errors, will provide more reliable estimation of the duration for transmission (or reception) of the remaining segments and ACK frame.

C. Modeling the transmission (or reception) process as SMDP

For purpose of analysis in this paper, the transmission (or reception) process of DAs system is characterized as infinite horizon discounted SMDP. The SMDP model consists of five elements namely: *decision epochs*, *state space*, *action space*, *transition probability*, and *rewards* [23]. These elements are defined as follow:

Decision epoch: It is the point in time when a sensor node executes action. Decision epochs are $T = \{t_1, t_2, t_3, \dots\}$.

State space: $s = \{s_1, s_2, s_3\}$. States are s_1 (transmitter sensor node), s_2 (receiver sensor node), and s_3 (other sensor nodes).

Action space: A_s is the allowable actions in current state s . $A_s = \{a_{i,j}, a_{j,i}\}$; where $a_{i,j}$ denotes action in respect of transition from current state i to next state j , and $a_{j,i}$ denotes action in respect of transition from current state j to next state i .

Transition probability: Choosing an action a in current state s at current decision epoch t , the system state j at the next decision epoch is determined by the probability distribution $p(j|s, a)$.

Rewards: The immediate discounted rewards function, $r(s, a)$, is given by

$$r(s, a) = z(s, a)$$

$$+ \int_0^{\infty} \sum_{j \in S} \left[\int_0^{\xi} e^{-\alpha t} c(j', s, a) p(j'|t, s, a) dt \right] \cdot F(\gamma | s, a) d\gamma \quad (15)$$

The times between decision epochs in the SMDP model are exponentially distributed with positive rate parameter, $\lambda(s, a)$; thus, $F(t|s, a) = 1 - e^{-\lambda(s, a)t}$. Exponential distribution is used in SMDP analysis to model the time until an event occurs in a process. Moreover, state transition occurs at the end of sojourn time in current state, and the system's process generates sequence of rewards as it makes transition from state to state. The corresponding transition rate diagram is presented in Fig. 4; where λ and μ denote positive rate parameters. These rate parameters are constants as the rates do not change with time. When "Other Nodes" (s_3) broadcast while data transmission (or reception) is ongoing between nodes s_1 and s_2 , there will be data corruption at the receiver sensor node at cost of additional transmission time and energy.

During exchange of the directional RTS/CTS frame between the transmitter and receiver sensor nodes, all sensor nodes in the DA's coverage area will receive the RTS frame from the transmitter sensor node and the CTS frame from the receiver sensor node. While transmission (or reception) of data frames is ongoing between the receiver and transmitter sensor nodes, it is expected that no sensor node(s) within the directional coverage area should be able to communicate with either the transmitter or receiver sensor node (or both); otherwise, data corruption will occur.

In this paper, reward represents earning from energy-efficient transmission (or reception) by sensor nodes. The immediate reward, $r(s, a)$, received in a current state consists of (i) lump sum reward, $z(s, a)$, and (ii) accumulated rewards at continuous reward rates, $c(j', s, a)$. When sensor node's system process chooses action, it either receives a lump sum reward or pays a lump sum cost. Moreover, the system accrues reward (or incurs cost) at continuous rate as long as the natural process occupies state j' , and action a was chosen in State s at the preceding decision epoch. For purpose of illustration, the unit of reward is milli Joule (mJ). Reward of +1 for example represents earnings of 1mJ (i.e. efficient energy utilization), and a reward of -1 represents loss of 1mJ (i.e. inefficient energy utilization).

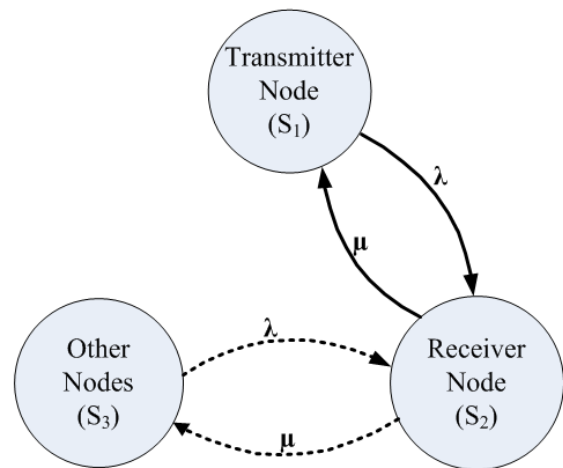


Fig.4. Transition rate diagram for the SMDP model.

Subsequently, rewards are specified as follows: (a) lump sum reward associated with transition out of States s_1 is equal to 5, and the system's process accumulates rewards between the decision epochs at continuous reward rate of 20; (b) lump sum reward associated with transition out of States s_2 is equal to 2; and the system's process accumulates rewards between decision epochs at continuous reward rate of 10; and (c) lump sum reward associated with transition out of State s_3 is equal to 1; and the system's process accumulates rewards between decision epochs at continuous reward rate of 1. Similarly, the cost of transiting from current state to a next state upon expiration of sojourn time is specified as follows: (a) lump sum cost associated with transition out of States s_1 is equal to -1 and the system's process accumulates cost (i.e., negative rewards) between decision epochs at continuous reward rate of -1; (b) lump sum cost associated with transition out of States s_2 is equal to -1, and the system's process accumulates cost between decision epochs at continuous reward rate of -1; and (c) lump sum cost associated with transition out of States s_3 is equal to -10, and the system's process accumulates cost between decision epochs at continuous reward rate of -25.

The expected total discounted reward is computed by

$$r(s, a) = z(s, a) + \int_0^{\infty} \sum_{j \in S} \left[\int_0^{\xi} e^{-\alpha t} c(j', s, a) p(j'|t, s, a) dt \right] \cdot F(\gamma | s, a) d\gamma \quad (15)$$

where $p(j'|t, s, a)$ is the transition probability of the natural process, $F(\gamma|s, a)$ is the sojourn time distribution in State s and α denotes the discount rate [23]. In this SMDP model, the natural process does not change state until the next decision epoch; hence, $p(j'|t, s, a)$ is set to 1. For stationary policy therefore, the infinite horizon sum of expected total discounted reward, starting from current state is given by

$$v_{\beta}^{d^{\infty}}(s) = z(s, a) + \sum_{j \in S} p(j|s, a) \int_0^{\infty} e^{-\beta t} F(t|s, a) dt \cdot v_{\beta}^{d^{\infty}}(j) \quad (16)$$

where $p(j/s,a)$ denotes transition probability of the embedded MDP, $v_{\beta}^{a^*}(j)$ is the infinite horizon sum of expected total discounted reward, starting from the next state j . The optimal equation for deterministic Markovian policy in this model is subsequently given by

$$v_{\beta}^*(s) = \max_{a \in A_s} \left\{ \begin{aligned} & z(s,a) \\ & + \sum_{j \in S} p(j|s,a) \int_0^{\infty} e^{-\beta t} F(t|s,a) dt v_{\beta}^{\pi}(j) \end{aligned} \right\}. \quad (17)$$

where $v_{\beta}^*(s)$ represents the infinite-horizon maximum sum of expected total discounted reward in current state s when action a was chosen, and $v_{\beta}^{\pi}(j)$ is the infinite-horizon sum of expected total discounted reward of following policy π starting from state j . The optimality and convergence of Equation (17) to the average optimal value of sum of expected total discounted rewards in current states starting from state 1 over infinite horizon is proved in [24].

IV. RESULTS OF NUMERICAL ANALYSIS AND DISCUSSION OF RESULTS

This section presents results of numerical analysis and discussion of the results. There are three directional antennas in the DAs system, T_{SIFS} is equal to $10\mu s$, and $(SNR)_{dB}$ ranges from 0 to 100 [25]. In addition, $\gamma_1=100\mu s$, $\gamma_2=75\mu s$, $\gamma_3=50\mu s$, $\gamma_4=25\mu s$; $a=0, b=25, c=50, d=75$, and $e=100$. Moreover, β is in the range $0 < \beta \leq 1$.

Recall in this paper that every neighbouring sensor node that receives the effective duration value uses this information to set up its duty cycling. In Fig. 5, the SNR is the primary factor for estimating the effective DV in the absence of transmission error(s). It is important to note that as the value of SNR increases the transmitter can use higher data rates and complex modulation scheme. For example, when SNR values are 10, 50, 75, and 90, the estimated effective DV are $688\mu s$, $663\mu s$, $638\mu s$, and $613\mu s$ respectively; while the initial DV based on the IEEE 802.11 implementation remains $598\mu s$. These results demonstrate that as the quality of signal increases the effective DV for transmission (or reception) of data and ACK frames reduces and tends towards the initial predicted DV. Consider the case when SNR is 90 for example, the effective DV is $613\mu s$, while initial predicted DV is $598\mu s$. When transmission error(s) exist however (Fig. 6), the values of the initial DV remains $598\mu s$, but the estimated effective DV broadcast in the directional CTS frame to the transmitter sensor node as well as the neighbouring sensor nodes of the receiver sensor nodes depends on the prevailing value of SNR and the provision made for re-transmissions of the corrupted segments. For example, when SNR values are 10, 50, 75, and 80, the estimated effective DV are $1884\mu s$, $1859\mu s$, $1834\mu s$, and $1809\mu s$ respectively for case $\beta=0.5$. Moreover, when SNR values are 10, 50, 75, and 80, the estimated effective DV are $2482\mu s$, $2457\mu s$, $2432\mu s$, and $2407\mu s$ respectively for

case $\beta=1.0$. Recall that β denotes the proportion of initial DV provided for re-transmission of corrupted segments.

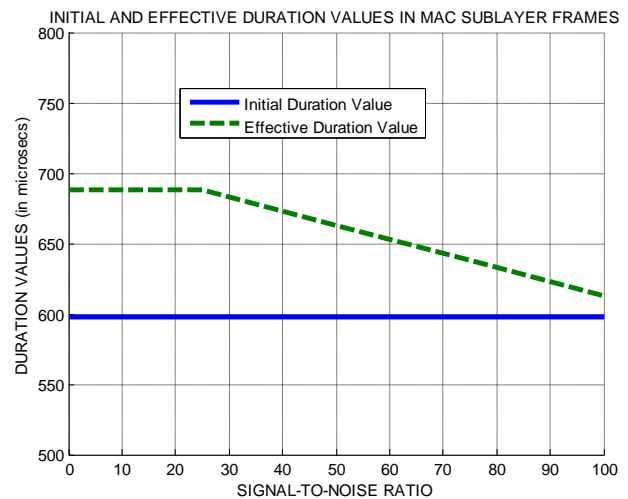


Fig.5. Initial and estimated effective duration values (without interferences during ongoing transmission).

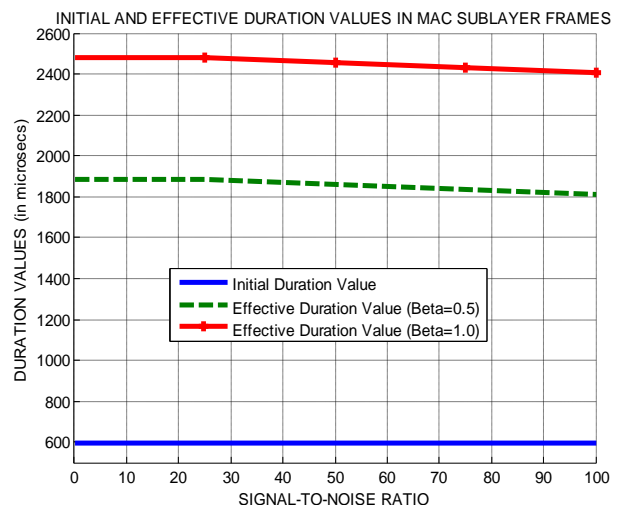


Fig.6. Initial and estimated effective duration values (with interferences during ongoing transmission).

The results of the analysis of the SMDP model are presented in Table III, Figs. 7 and 8, where Options A and B are defined as follow.

Option A --The transmitter and receiver sensor nodes successfully exchange directional RTS/CTS frame and commence transmission (or reception) of data and acknowledgment frames. The neighbouring sensor nodes of the receiver sensor node use the estimated effective DV to set up their duty cycling.

For this case, there are no interferences and no data corruption. Onboard energy resource of the wireless sensor nodes are efficiently utilized for data transmission (or reception).

Option B --The transmitter and receiver sensor nodes successfully exchange directional RTS/CTS frame and commence transmission (or reception) of data and acknowledgment frames. The neighbouring sensor nodes

of the receiver sensor node use the initial duration value to set up their duty cycling.

For this case, there can be interferences from neighbouring sensor nodes, and data corruption may occur. Onboard energy resource of the wireless sensor nodes may be inefficiently utilized for data re-transmissions.

In the SMDP- based model presented in this paper, the optimal values represent the maximum value of sum of expected total discounted rewards in all states, starting from State 1 (s_1). The expected total discounted rewards in each state and sum of expected total discounted rewards starting from State 1 (s_1) are presented in Table V.

Whereas *Option A* earns expected total discounted reward of 5600mJ starting from State 1, *Option B* earns 3700mJ. Similarly, *Option A* earned higher expected total discounted rewards of 291.8mJ when analysis starts from State 2, while *Option B* earns 192.3mJ. Moreover, whereas *Option A* earns a reward of 0mJ when analysis

starts from State 3, *Option B* earns a reward of -24.8mJ. Based on reward specifications in this paper, the higher rewards imply that *Option A* offers higher level of energy-efficiency in data transmission (or reception). Fig.7 graphically presents expected total discounted reward in current states at decision epochs starting from State 1. Whereas *Option A* earns 5600mJ at State 1, *Option B* earns 3700mJ. *Option A* also earns higher expected total discounted rewards of 291.8mJ at State 2, while *Option B* earns 192.3mJ. Moreover, whereas *Option A* earns 0mJ at State 3, *Option B* earns -24.8mJ. The graphs in Fig. 8 represent sum of expected total discounted rewards in all states at decision epochs starting from State 1. Whereas *Options A* earns sum of expected total discounted rewards of 5891.8mJ in State 1, *Option B* earns 3867.5mJ. When analysis is based on the system's process starting from State 2, *Option A* earns 291.8mJ in rewards while *Option B* earns 167.5mJ.

Table III: Sum of expected total discounted rewards earned starting from State 1
 (For illustration purpose, value of reward is in mJ)

Decision epochs	1			2		3	
	States/Options	1(s_1)	2(s_2)	3(s_3)	Total	Maximum	
$v_1(s)$	A	5600	291.8	0	5891.8	5891.8	
	B	3700	192.3	-24.8	3867.5		
$v_2(s)$	A		291.8	0	291.8	291.8	
	B		192.3	-24.8	167.5		
$v_3(s)$	A			0	0	0	
	B			-24.8	-24.8		

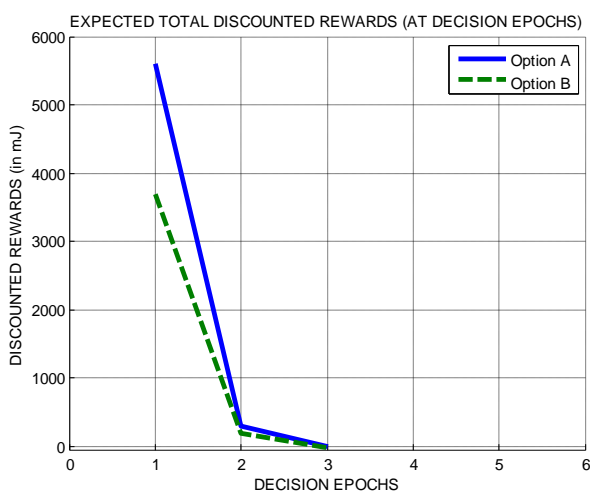


Fig.7. Expected total discounted reward in current states at decision epochs.

Furthermore, *Option B* earns -24.8mJ while *Option A* earns 0 mJ when analysis starts from State 3.

In this SMDP framework, optimal values are the maximum sum of expected total discounted rewards in all states at decision epochs starting from State 1. Through optimal analysis, it is shown that *Option A* offers optimal values in all states at decision epochs starting from State 1. The implication of these results is that the approach in *Option A* offers optimal energy-efficient data transmission (or reception).

A. Contributions of this paper

The contributions of this paper are summarized as follow:

- The paper presents a new approach for estimating effective duration value in MAC sub-layer frames of IEEE 802.11 using the initial duration value in transmitted frames.
- The paper presents an energy-efficient MAC protocol using directional antennas in IEEE802.11-based wireless sensor networks
- The contributions in (a) and (b) above will reduce interferences from neighbouring sensor nodes in the directional coverage areas of receiver sensor node, thereby providing a basis for design and implementation of energy-efficient wireless sensor networks.

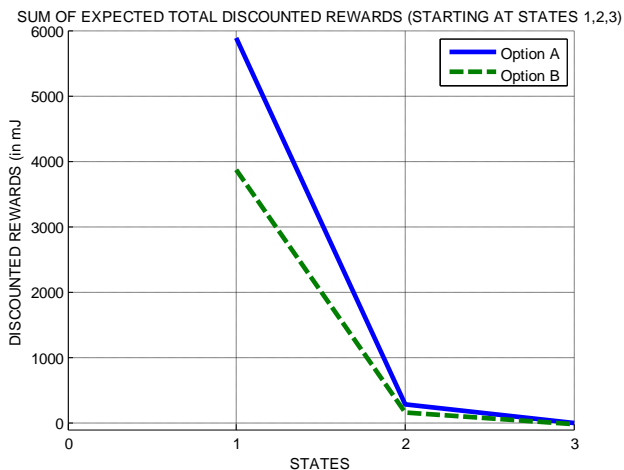


Fig.8. Sum of expected total discounted rewards starting at States 1, 2 and 3.

V. CONCLUSION

The problem of interference(s) from neighbouring sensor nodes in the directional coverage areas of receiver sensor nodes that may lead to inefficient energy utilization for data transmission (or reception) was investigated in this paper. The research was based on the IEEE 802.11 standard in which every transmitted frame in the MAC sub-layer has duration value (DV). The DV indicates the time needed to transmit remaining segments and acknowledgement frame. Since packets corruption, poor link quality and multipath propagation may affect initial predicted transmission time during directional RTS/CTS frame exchange which may lead to inefficient duty cycling by neighboring sensor nodes, the paper presented a novel energy-efficient MAC protocol using directional antennas in IEEE 802.11-based wireless sensor networks. This MAC protocol includes a new methodology for estimating effective DV for MAC sub-layer frames. The efficacy of this approach was tested via numerical analysis which was implemented in Visual C++ and MATLAB Software. The results obtained show that this new MAC protocol will further improve energy efficiency by reducing interferences from neighbouring sensor nodes in the directional coverage areas of receiver sensor node, thereby providing a basis for design and implementation of energy-efficient wireless sensor networks.

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